AD NUMBER

AD852601

LIMITATION CHANGES

TO:

Approved for public release; distribution is unlimited. Document partially illegible.

FROM:

Distribution authorized to U.S. Gov't. agencies and their contractors; Critical Technology; MAY 1969. Other requests shall be referred to Air Force Armament Laboratory, ATWG, Eglin AFB, FL 32542. Document partially illegible. This document contains export-controlled technical data.

AUTHORITY

afatl ltr, 4 oct 1972

AFATL-TR-69-42

Analytic and Experimental Interior Ballistics of Closed Breech Guns

by

Otto K. Heiney, 1st Lt, USAFR

MAY 1969

AIR FORCE ARMAMENT LABORATORY
AIR FORCE SYSTEMS COMMAND • UNITED STATES AIR FORCE
EGLIN AIR FORCE BASE, FLORIDA

ANALYTIC AND EXPERIMENTAL INTERIOR BALLISTICS OF CLOSED BREECH GUNS

by

Otto K. Heiney, 1st Lt, USAFR

FOREWORD

This report has been generated under the interior ballistic analysis portion of Project 62405094 2560. It is an extension of a propellant actuated device interior ballistic formulism developed at the Jet Propulsion Laboratory (reference 1) at Pasadena, California, under NAS 7-100. The report was written by 1st Lt O. K. Heiney, USAFR, attached to the Air Force Armament Laboratory [AFATL (ATWG)] for an annual active duty tour. Assistance of the personnel of both AFATL (ATBA) and the Armament Development and Test Center [ADTC (ADTVF-2)] with the formulation and execution of the computer program is gratefully acknowledged.

Information in this report is embargoed under the Department of State International Traffic in Arms Regulations. This report may be released to foreign governments by departments or agencies of the U. S. Government subject to approval of the Air Force Armament Laboratory (ATWG), Eglin Air Force Base, Florida, or higher authority within the Department of the Air Force. Private individuals or firms require a Department of State export license.

This technical report is approved.

CHARLES K. ARPKE, Lt Colonel, USAF
Acting Chief, Weapons Division

ABSTRACT

A closed breech incremental interior ballistic formulism is presented along with a Fortran 4 computer program which utilizes the system. Typical input and output data, both plotted and tabular, are included. A unique characteristic of the system is that it avoids the inaccuracies associated with approximate analytic propellant regression expressions in that regression rates are determined by a tabular routine. Various pressure gradient expressions are investigated. Correlation of the mathematical model and computer predictions to experimental device firings are presented. A shock-driven deflagration effect which may be initiated during the ignition transient is described and a postulated correlation parameter defined.

(The reverse of this page is blank.)

CONTENTS

ILLUSTRATIONS AND TABLES

ILLUSTRATIONS AND TABLES (CONTINUED)

NOMENCLATURE

A = Bore Area
a = Acceleration
C = Arbitrary Constant
C_v = Constant Volume Gas Specific Heat
C_w = Charge Weight
E_G = Kinetic Energy of Propellant Gas
F = Force
F_p = Impetus of Propellant
g = Acceleration Due to Gravity
m_A = Pseudo Mass of Propelled Device
m_p = Mass of Propelled Device
M = Mach Number
N_B = Propellant Burned
P_{AV} = Average Plenum Pressure
P_o = Total Pressure
P_s = Shot Base Pressure
r = Regression Rate of Propellant
R = Gas Constant
S_B = Burning Surface of Propellant
T = Gas Temperature
T_o = Isochoric Flame Temperature of Propellant
V = Shot Velocity
v_c = Initial Chamber Volume
v = Gas Velocity
X = Distance from Shot Base to X_o
X_o = Initial Shot Reference
x = Arbitrary Reference Behind Shot
β = Heat Loss Factor
γ = Specific Heat Ratio of Propellant Gas
δ = Density Distribution Factor
η = Covolume of Propellant Gases
ρ = Average Density of Gas
ρ_p = Density of Propellant
ρ_0 = Breech Gas Density
ρ_s = Density of Gas at Projectile
ϕ = Pressure Gradient Factor
ω_0 = Initial Propellant Web
Δ = Burning Surface Factor

(The reverse of this page is blank.)

SECTION I

INTRODUCTION

The basic interior ballistic problem of any closed breech gun system is to determine the energy release and corresponding pressure generated by the burning of propellant in a variable volume. From the energy balance and the equation of state, the pressure-time or pressure-travel as well as muzzle velocity and piezometric efficiency of the system is established, thus providing the complete ballistic solution.

The results of the analysis, Section II, are essentially contained in equations (9) and (26) which are in an incremental form specifically tailored for machine computation. Program listing and typical results are presented in Section III.

The analysis in Section II considers first the energy balance of the system in paragraph A, Section II. In paragraph B, Section II, the kinetic energy in the propellant gas is determined. Also investigated are various expressions for the pressure gradient from the breech to the moving shot. In paragraph C, Section II, the constant burning surface of single perforate propellant is demonstrated and a tabular regression routine defined.

Section IV illustrates the comparison of the presented model to experimentally measured pressure histories of device firings. The experimental set-up is described, and a shock-driven deflagration phenomenon that was encountered is defined.

SECTION II

ANALYSIS

ENERGY BALANCE

The Noble-Abel equation of state is:

$$P(V - \eta) = nRT \tag{1}$$

Where η is the "covolume" of the propellant and has the units of volume/mass which arises due to the fact that the combustion products are not perfect gases.

The central property of the propellant is its "impetus," F_p, which is qualitatively similar to the c* of rocket propellants.

$$F_p = RT_o \tag{2}$$

Where T_o is the isochoric flame temperature of the propellant gases and F_p has units of specific energy (ft-lb/lb).

The energy equation, following the techniques in reference 2, for the system will be

$E_1 = E_2 + E_3 + E_4$, where

E_1 = energy put in system from propellant combustion
E_2 = translational energy of piston
E_3 = heat loss to walls
E_4 = kinetic energy of unburned propellant and propellant gases
A = cross section of bore
$\forall_c$ = initial chamber volume
X = distance from X_o to piston base.

The instantaneous free chamber volume is a function of the initial chamber volume plus the barrel volume exposed by shot motion minus volume occupied by unburnt propellant and combustion gases. Combining equations (1) and (2) then gives

$$P\left[(v_c + AX) - \frac{(C_w - N_b)}{\rho_p} - \eta N_b\right] = \frac{N_b F_p T}{T_o} \tag{3}$$

Thermal and chemical energy released by propellant will be

$$E_1 = N_b C_v (T_o - T) \tag{4}$$

Translational energy of the piston will be

$$E_2 = 1/2\ m_p\ \dot{V}^2$$

The heat loss of the gases is proportional to the distance traveled, which (following reference 3) is roughly proportional to the square of the velocity. We can, to a good approximation, say that

$$E_3 = 1/2\ \beta m_A\ V^2$$

Using the expression developed in paragraph B, below, for the kinetic energy contained in the accelerating gas and unburned propellant, we may write

$$E_4 = 1/2\ \frac{C_w V^2}{g\delta}$$

We may define

$$m_A = m_p + \frac{C_w}{\delta g}$$

Then

$$E_2 + E_3 + E_4 = (1 + \beta)(1/2) m_A\ V^2 \tag{5}$$

Defining Y by equation (6)

$$(Y - 1) = \frac{R}{C_v} = F_p / C_v T_o \tag{6}$$

Then from equations (4), (5), and (6)

$$N_b F_p (1 - T/T_o) = 1/2\ (Y - 1)\ (1 + \beta)\ m_A\ V^2 \tag{7}$$

The temperature ratio is eliminated by the introduction of the equation of state to give the fundamental ballistic equation

$$N_b F_p - (\gamma - 1)(1 + \beta)\frac{m_A}{2} V^2 = P_{AV}\left[(v_c + AX) - \frac{(C_w - N_b)}{\rho_p} - \eta N_b\right] \quad (8)$$

or as a differential form of equation (8) is more convenient for incremental computation, differentiating, and taking differential chamber volume changes due to charge regression as second order; this is

$$\frac{dP_{AV}}{dt}\left[(v_c + AX) - \frac{(C_w - N_b)}{\rho_p} - \eta N_b\right] = \frac{dN_b}{dt} F_p - (\gamma - 1)(1+\beta)\, m_A \frac{dV}{dt}\frac{dx}{dt} - P_{AV} A \frac{dx}{dt} \quad (9)$$

Equation (9) provides the basis for the complete incremental interior ballistic solution; however, two additional functions are necessary to provide required relationship in the above formulation.

The first is projectile velocity as a function of average chamber pressure, or $V = f(P_s, t, m_p)$

This relation is determined in paragraph B below. The second expression required is a value for the surface exposed to burning as a function of web fraction burned.

$$N_t = f(P_{AV}, t)$$

which is covered in paragraph C below.

PRESSURE GRADIENT AND GAS KINETIC ENERGY

The determination of the pressure gradient in the barrel is central to the ballistic solution, as the velocity of the shot is a function of the pressure at the shot while equation (9) gives a value for P_{AV}. The density distribution in the gas is also required to give a value for the gas kinetic energy. The density and pressure variations are determined for an average temperature in the combustion chamber of T_o and also for an average temperature of $7/10\ T_o$. This problem was first studied by La'Grange and his approach introduces the analysis.

$$\frac{\partial \rho}{\partial t} + \frac{\partial}{\partial x}(\rho v) = 0 \quad (10)$$

and assuming constant density

$$\frac{\partial \rho}{\partial x} = 0$$

results in equation (10) being separable with the result.

$$\frac{1}{\rho}\frac{\partial \rho}{\partial t} = -\frac{\partial v}{\partial x} = C \tag{11}$$

Equation (11) is integrated with the boundary conditions

BD 1. $X = X_o = 0,\ v = 0$

BD 2. $X = X \quad ,\ v = V = \frac{dx}{dt}$

$$\int_o^v dv = C \int_o^x dx$$

$$v = Cx \tag{12}$$

at boundary 2

$$C = \frac{1}{X}\frac{dX}{dt}$$

then

$$v = \frac{x}{X}\frac{dX}{dt} \tag{13}$$

It is thus seen the constant density assumption of La'Grange will directly result in a linear velocity profile for the gases, equation (13). Constant density is then a sufficient condition for velocity linearity, though not necessarily a necessary condition.

The kinetic energy in the gas using the above approach is then

$$E_G = 1/2 \int_o^x A\rho v^2\, dx = \frac{A\rho}{2} V^2 \int_o^x \frac{x^2}{X^2}\, dx = (1/2)\ (1/3)\ A\rho X V^2$$

but

$$A\rho X = \frac{C_w}{g}$$

then

$$E_G = (1/2)\ (1/3)\ \frac{C_w V^2}{g} = 1/2\ \frac{C_w V^2}{\delta g} \qquad (14)$$

where

$\delta = 3$ for the La'Grange solution.

The factor δ was introduced by Hirschfelder (reference 3) in his extension of the work of Kent (reference 4) who allowed the gas density to vary and solved for δ as a function of the charge to projectile mass ratio.

Solutions of the form $\delta = f\ (C_w/m_p g)$

are useful for the approximate closed form ballistics of Hirschfelder but are of less utility for incremental computer solvable interior ballistic system discussed here. The results of La'Grange ($\delta = 3$) essentially state that the energy in the accelerating gas is equivalent to 1/3 of the gas mass traveling at shot velocity. This is a good approximation at velocities where the gas density is almost constant. It falls apart, as would be expected, at velocities where the density is no longer uniform.

For incremental computations, δ is most effectively formulated as a function of shot velocity. To do this, it is first necessary to describe the density variation behind the projectile as a function of shot velocity. It is then assumed that a linear velocity gradient exists behind the shot and also that isentropic flow relations may be used during an interval to describe the flow behind the shot.

This requires that the flow during the short interval considered be looked upon as "quasi-isentropic." From reference 5, the density ratio is then

$$\rho/\rho_o = \left(1 + \frac{\gamma - 1}{2}\ \frac{v^2}{gRT}\right)^{-1/\gamma - 1} \qquad (15)$$

The question then arises as to what temperature should be used to define the speed of sound in the environment of the burning gases. An upper bound for this temperature would be the isochoric flame temperature of the gases T_o; a reasonable lower bound would be 7/10 T_o. The analysis is then conducted with the above values as bounds.

The results of equation (15) are plotted on Figure 1 for a $\gamma = 1.222$ and an $RT_o = 375{,}000$ ft-lb/lb.

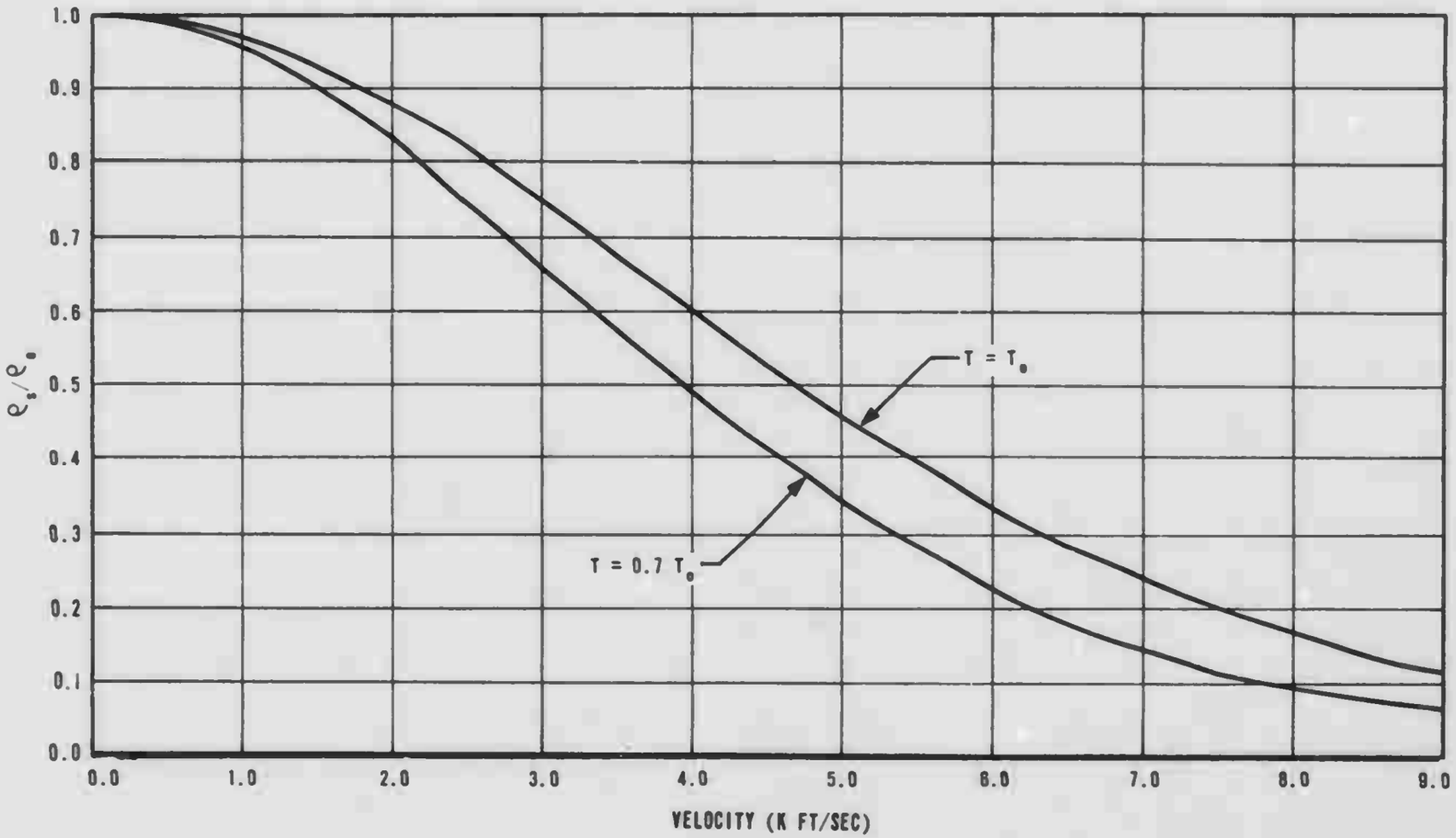


Figure 1. Density Gradient as Function of Shot Velocity.

The energy increment in a small control volume of gas will then be

$$E_I = 1/2\ \rho_N\ V_N^2\ A\Delta X_N$$

$$E_G = \frac{A\rho_o}{2} \sum \frac{\rho_N}{\rho_o} V_N^2\ \Delta X_N = 1/2\ \frac{C_w}{g\delta}\ V^2 \qquad (16)$$

The value of δ, for a given velocity, is determined by performing the numerical summation of equation (16) on a digital computer. The results of this procedure are plotted on Figure 2. As would be expected at low velocities, the value of δ approaches 3.0. The results of δ as a function of velocity is then fed into the main ballistic program as data and allows for the computation of the value of the kinetic energy of the gas.

PRESSURE GRADIENT

The necessity of relating $P_s = f(P_{AV})$ has been explained above. The approach used here is to relate P_s to P_o by two independent methods and then empirically determine a P_{AV} to P_s relationship. A value for the ratio of P_s/P_o may be obtained by means of the "quasi-isentropic" assumption used for densities above.

$$P/P_o = \left(1 + \frac{\gamma - 1}{2} \frac{v^2}{gRT}\right)^{-\gamma/\gamma-1} \qquad (17)$$

The results of this relation are plotted on Figures 3 and 4 for the temperatures $T = T_o$ & $T = .7T_o$ respectively.

Another approach to the pressure gradient solution would be to assume a constant temperature process. In which case Euler's equation and the equation of state will give:

$$P = \rho RT \qquad (18)$$

$$vdv = -\frac{dp}{\rho} \qquad (19)$$

combining equations (18) and (19) and integrating

$$\int_o^v vdv = -\int_{P_o}^{P_s} \frac{RT}{P}\, dP$$

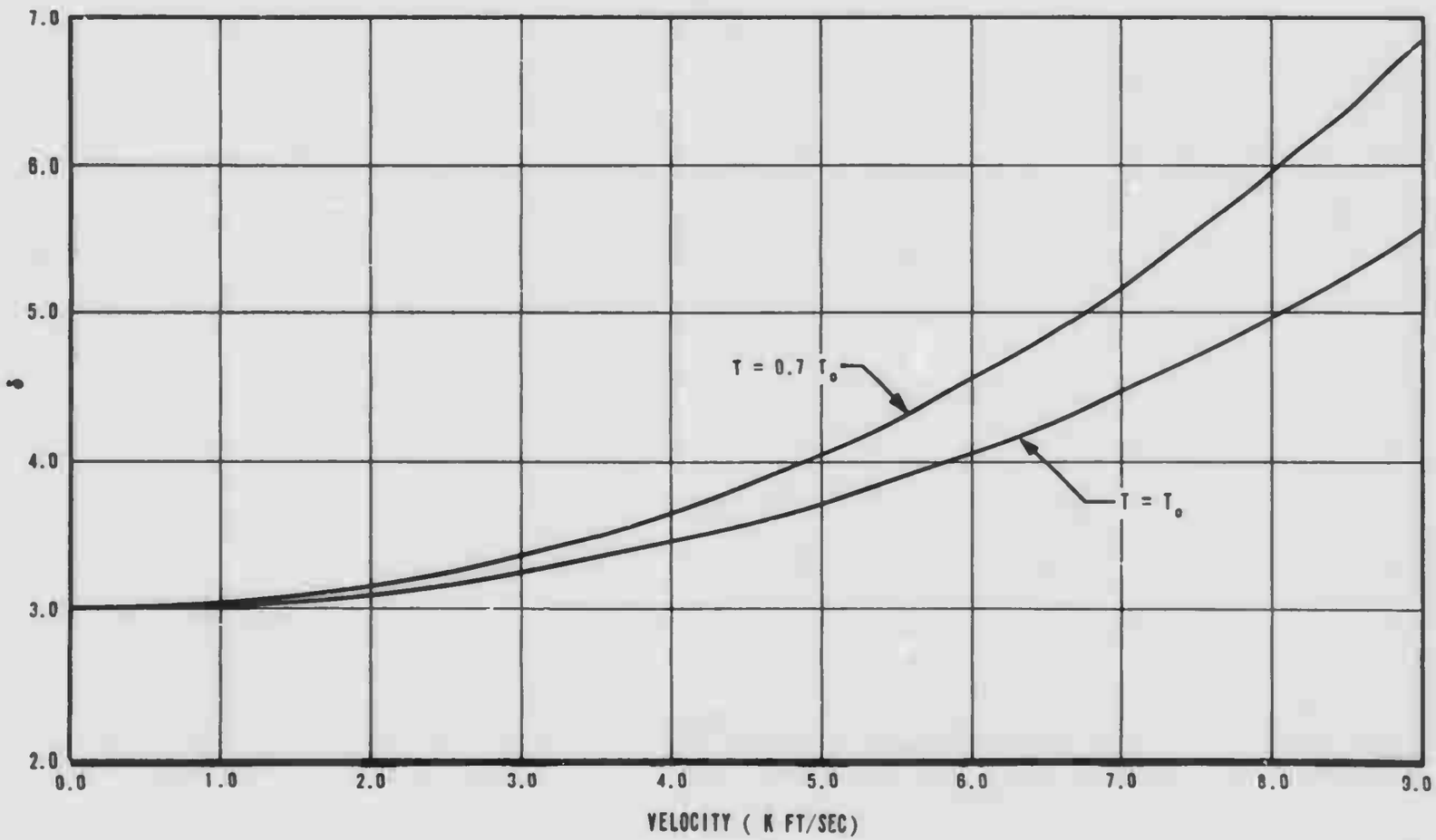


Figure 2. δ Value as Function of Projectile Velocity.

$$\frac{V^2}{2} = -RT \ln (P_s - P_o) \tag{20}$$

The results of equation (20) are also plotted on Figures 3 and 4. The constant temperature equation predicts a lower shot pressure than the quasi-isentropic relation. To relate P_s to P_{AV} then, a heuristically reasonable approach would be to assume that a relation of the form

$$P_s/P_{AV} = \left(1 + \frac{\gamma - 1}{2\phi} \frac{v^2}{gRT}\right)^{-\gamma/\gamma-1} \tag{21}$$

with $\phi > 1$ would be satisfactory. To investigate this possibility, it is necessary to develop a value for P_{AV} which has only the gas acceleration energy accounted for. This is done as follows:

$$P_o v_c - \frac{mv^2}{2\delta} = P_{AV} v_c$$

$$P_{AV}/P_o = 1 - \frac{V^2}{2\delta g F_p (T/T_o)} \tag{22}$$

Using the expression developed for $\delta = f(v)$ with $\phi = 1.5$ the combined results of equations (21) and (22) will give a value for P_s/P_o which is again plotted on Figures 3 and 4. It is seen that this value of ϕ gives consistent results for both temperature extremes. It is used in the interior ballistic formulism to relate the average pressures generated by equation (9) to the pressure at the base of the shot required for the equation of motion, as shown below.

$$V = V_o + at \tag{23}$$

$$a = \frac{P_s A}{m_p} \tag{24}$$

$$P_s = \left[1 + \frac{\gamma-1}{2\phi} M^2\right]^{-\gamma/\gamma-1} P_{AV} \tag{25}$$

then

$$V = V_o + \frac{A P_{AV}}{m_p} \left[1 + \frac{(\gamma-1)}{3} \frac{V^2}{g\gamma F_p}\right]^{-\gamma/\gamma-1} \tag{26}$$

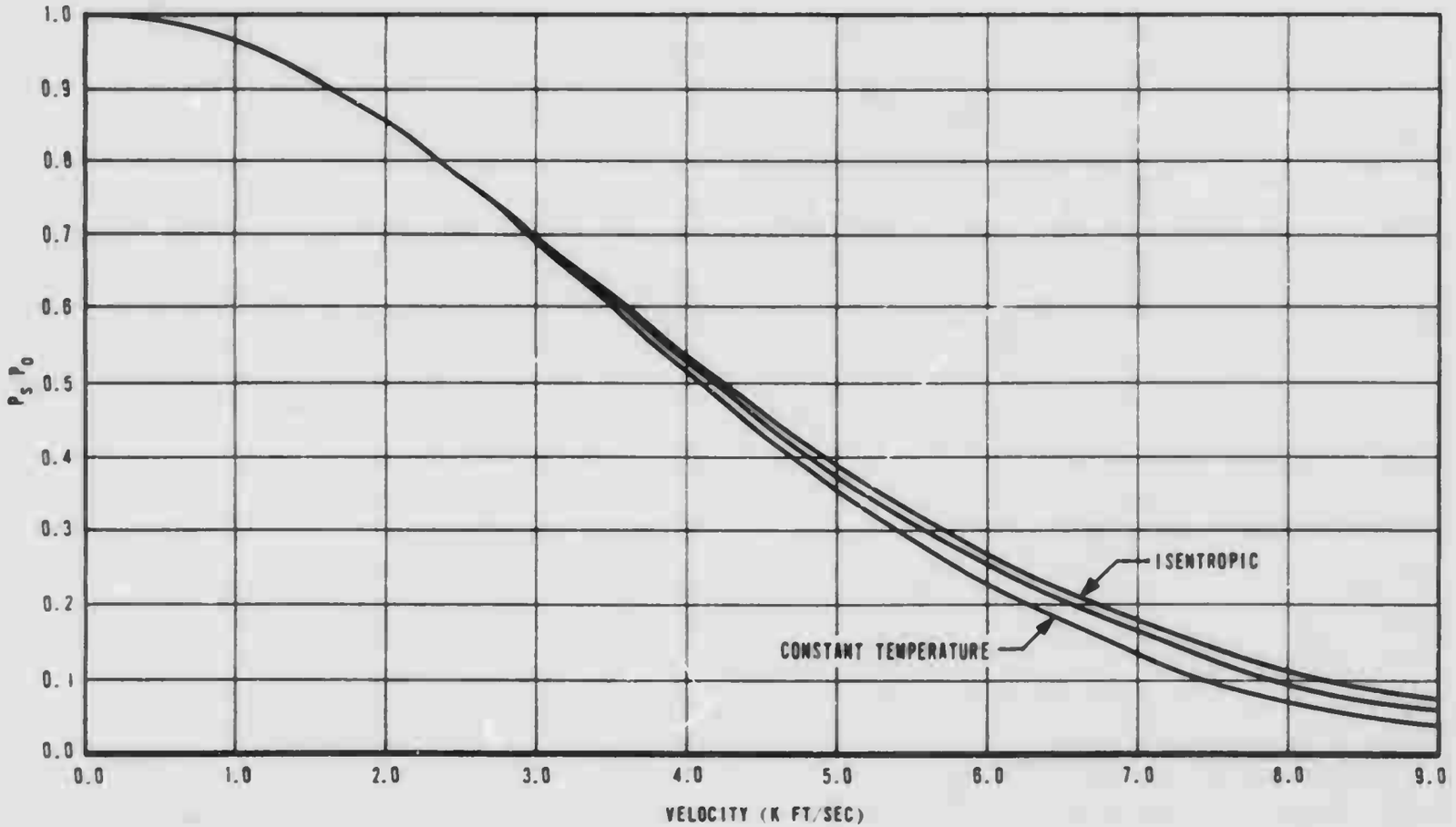


Figure 3. Shot Pressure to Static Pressure Ratio, $T = T_o$.

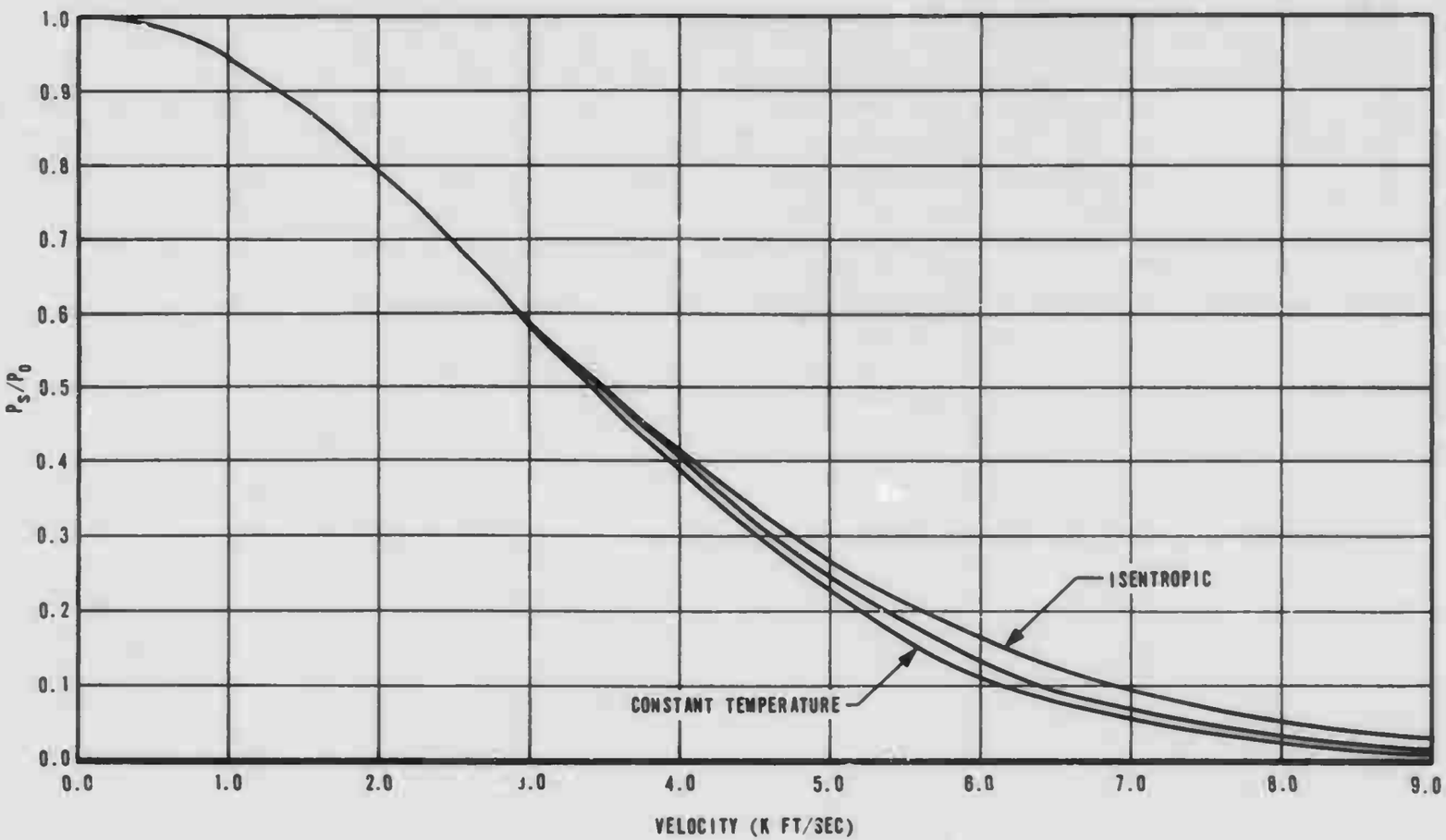


Figure 4. Shot Pressure to Static Pressure Ratio, $T = .7T_0$

Equation (26) thus provides the necessary relationship to solve for the projectile motion once the average chamber pressure is shown. The final information required is an expression for the total rates of combustion.

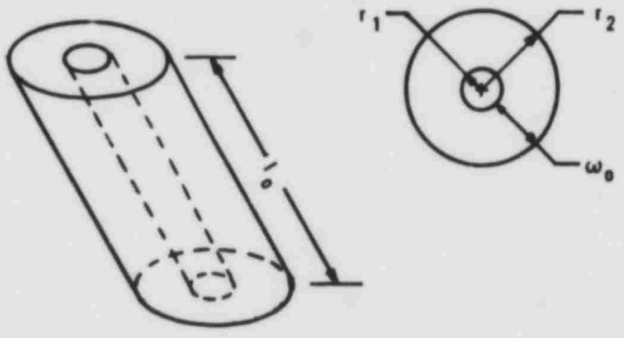
GAS PRODUCTION

The time rate of gas production is simply written as

$$\frac{dN_B}{dt} = r\, S_B\, \rho_p$$

In most prior interior ballistic formulisms the approximation $r = BP^n$ with constant N has been made. Frequently, for closed form solutions, the often questionable assumption that $N = 1$ is made. For a numeric solution, however, no approximations are required. Burning rates as a function of pressure, for currently used propellants, are tabulated in reference 7. These values are read into the program as data, and a tabular interpolation routine in the program determines the correct burning rate. Thus all recourse to Vielle's law has been avoided.

The surface of burning of single perforate propellants is very nearly constant as shown below. For other forms, such as cord, disk, and multiperforate, various empirical "form" functions exist to evaluate burning surface as a function of unburned web. These functions are covered in detail in references 3, 6, and 8.



$\omega_o = r_{2,o} - r_{1,o}$ for a propellant with $\frac{\omega_o}{l_o} \ll 1$.

Burning surface for each grain will be

$$S_{I,o} = 2l_o\, \pi\, (r_2 + r_1)$$

after a burning increment of Δr

$$S_{I,t} = 2\, l_o \pi \left([r_2 - \Delta r] + [r_1 + \Delta r] \right) = 2\, l_o\, \pi (r_2 + r_1)$$

thus at all times the burning surface is constant.

Volume of grain = $l_o\, \pi (r_2^2 - r_1^2)$

N' = Number of grains/unit mass

Then the burning surface/unit mass of the propellant will be

$$\frac{S_B}{C_w} = \frac{S_I N'}{\rho_p V_o N'} = \frac{2\, l_o\, \pi (r_2 + r_1)}{\rho_p\, l_o\, \pi (r_2 - r_1)(r_2 + r_1)} = \frac{2}{\rho_p\, \omega_o}$$

or

$$S_B = \frac{2}{\rho_p\, \omega_o}\, C_w \qquad (27)$$

Thus equations (9), (26), and (27) plus burning rate data provide the relationships necessary to solve for peak pressure, muzzle velocity and complete pressure-time, pressure-travel, and velocity-travel of any type of closed breech weapon.

SECTION III

COMPUTER PROGRAM

INPUT DATA AND USAGE

The input data for the program is in two parts. The first is the burning rate and impetus data for the propellant and may remain unchanged as long as one type of propellant is used. The second type card delineates the exact parameters for one given case and will change for each case. Propellant data are determined from the tables in references 7 and 9.

PROPELLANT CARDS.

1st CARD

Columns	Data	Decimal Point	Units
1-8	Impetus of Propellant	7	Ft-Lb/Lb
12-16	Specific Heat Ratio of Gases	13	Dimensionless
20-24	Density of Propellant	20	$Lb/In.^2$
28-31	Covolume of Gases	30	$In.^3/Lb$
33-36	Propellant Type	Alpha Meric	

2nd AND 3rd CARDS

20 reference pressures - 10 per card from 500 to 200,000 psia.

4th AND 5th CARDS

20 burning rates taken from reference 7 at pressures listed above.

6th AND 7th CARDS

20 reference velocities taken from 0 to 12,000 ft/sec.

8th AND 9th CARDS

Density distribution factor appropriate to propellant used and corresponding to velocity listed above. Values can be extracted from Figure 2.

PROBLEM CARDS.

Columns	Data	Decimal Point	Units
1-7	Bore Area	4	$In.^2$
8-14	Chamber Volume	11	$In.^3$
15-21	Projectile Weight	19	Lb
22-28	Barrel Length	27	In.
29-35	Propellant Web	31	In.
36-42	Heat Loss	40	Dimensionless
43-49	Charge Weight	44	Lb
50-56	Shot Start Press	56	$Lb/In.^2$

As many problem cards as desired may be loaded after the data for a given propellant and will be handled sequentially by the program. Data in the above format is illustrated in Table I.

RESULTS

Typical output is illustrated in Figures 5 and 6 and Tables II and III. Output includes time from propellant ignition, chamber pressure, shot base pressure, projectile velocity, chamber pressure slope, and distance traveled for a typical 25mm. The two sample cases are identical except for a decrease in charge weight in the latter. Subsequent to the case run, additional computations of extrapolated muzzle velocity to the specified barrel length, ballistic efficiency, and piezometric efficiency are also made. Following each printed output is the pressure-travel plot generated by the computer, which is also a standard output. It should be noted that the program is currently set up to run single perforate uninhibited propellant. For other forms, a proper form function, as mentioned above, must be inserted in the program. The heat loss factor, β, has a value of between .3 to .4 for a 25mm and will be somewhat larger for smaller bores and less for larger bore weapons.

COMPUTER PROGRAM

The FORTRAN Program listing used is given as Table IV. Run time on the 7094 computer is quite short (about .05 second per case). The program number is 958, and it is being maintained by ADTC (ADTVF-2).

TABLE I. PROGRAM INPUT: TYPI

Typical Propellant Cards	346180.	1.252 .	0603 29.	69 M-1
	300.	500. 7	00. 1000	. 15
	6000.	8000. 10	000. 20000	. 300
	.13	.2	.28 .3	8 .
	1.72	2.20	2.70 4.6	6.
	0.	500. 1	000. 1500	. 200
	5000.	5500. 6	000. 6500	. 700
	3.	3.	3.05 3.1	3.
	4.05	4.3	4.55 4.85	5.
Case Data Cards				
	.761 5.	74 .3	97 69.	.022
	.761 5.	74 .3	97 69.	.022

UT: TYPICAL PROPELLANT AND CASE DATA CARDS.

M-10					
1500.	2000.	2500.	3000.	4000.	5000.
30000.	40000.	50000.	70000.	100000.	200000.
.52	.68	.81	.96	1.2	1.45
6.7	8.3	9.6	12.2	15.8	25.
2000.	2500.	3000.	3500.	4000.	4500.
7000.	7500.	8000.	8500.	9000.	12000.
3.18	3.25	3.38	3.50	3.70	3.85
5.2	5.55	5.95	6.40	7.00	12.0
.22	.3 .20	4000.			
.22	.3 .18	4000.			

TABLE II. COMPUTER PRINTOUT OF 20MM PERFORMANCE 0.015 WEB.

SHOT WT.	CHARGE	WEB	H.LENGTH	CHB VOL	BORE AREA
.40	.200	.0220	64.0	5.74	.76

PROPELLANT USED IN DEVICE IS M-10

TIME	CHAMB PRES	TRAVEL	PROP BURNED	PRES SLOPE	VELOCITY	MS PRES
.0000	4000.0	.001	.0027	37466827.5	6.17	4000.0
.0000	4936.7	.004	.0060	44723334.8	13.78	4936.7
.0001	6054.8	.009	.0099	53923001.5	23.11	6054.7
.0001	7402.8	.018	.0146	63735680.1	34.52	7402.7
.0001	8996.2	.031	.0202	75458912.4	48.39	8995.9
.0001	10882.7	.048	.0267	87596429.3	65.17	10881.9
.0002	13072.6	.070	.0341	99010671.9	85.32	13070.9
.0002	15547.9	.099	.0427	111229256.8	109.28	15544.5
.0002	18328.6	.134	.0524	124020755.7	137.53	18322.1
.0002	21429.1	.183	.0635	137938537.0	170.55	21417.0
.0003	24877.6	.239	.0763	152968938.1	208.87	24855.9
.0003	28701.8	.309	.0909	167549065.0	253.06	28664.4
.0003	32840.5	.392	.1072	176296540.3	303.66	32827.6
.0003	37297.9	.492	.1251	179851798.3	361.01	37195.2
.0004	41744.2	.610	.1445	177555371.8	425.19	41631.6
.0004	46213.1	.748	.1652	167942188.3	496.08	45983.8
.0004	50431.7	.908	.1871	153298853.6	573.26	50061.6
.0004	54264.2	1.093	.2102	134076228.8	656.09	53733.5
.0005	57616.1	1.303	.2343	111180355.0	743.78	56879.4
.0005	60345.8	1.540	.2592	85908750.3	835.37	59405.4
.0005	62543.3	1.805	.2847	59766233.0	929.80	61253.2
.0005	64037.4	2.098	.3107	34247727.2	1026.00	62405.8
.0006	64843.6	2.420	.3369	10637852.3	1122.95	62887.1
.0006	65159.8	2.772	.3632	-10126502.8	1219.70	62755.0
.0006	64906.4	3.152	.3894	-27508989.0	1315.42	62092.0
.0006	64218.7	3.561	.4154	-41348734.5	1409.45	60993.7
.0007	63185.0	3.997	.4411	-51783295.0	1501.27	59558.5
.0007	61890.6	4.461	.4665	-59150429.2	1590.50	57879.3
.0007	60411.8	4.951	.4914	-63879372.3	1676.89	56038.3
.0007	58814.6	5.467	.5158	-66465412.9	1760.30	54105.2
.0008	57153.0	6.007	.5397	-67365417.6	1840.68	52135.2
.0008	55468.9	6.571	.5632	-66986763.1	1918.02	50170.8
.0008	53794.2	7.157	.5861	-65674414.0	1992.40	48243.3
.0008	52152.3	7.766	.6085	-63709183.9	2063.89	46374.6
.0009	50559.6	8.395	.6305	-61315026.5	2132.62	44579.1
.0009	49026.7	9.045	.6521	-58659080.6	2198.70	42865.5
.0009	47560.3	9.714	.6732	-55868375.1	2262.28	41238.3
.0009	46163.6	10.402	.6938	-53036011.8	2323.48	39698.7
.0010	44837.7	11.108	.7141	-50228279.9	2382.44	38245.8
.0010	43582.0	11.831	.7341	-47490913.4	2439.29	36877.2
.0010	42396.7	12.571	.7538	-44854102.1	2494.16	35589.3
.0010	41273.3	13.327	.7729	-42336798.0	2547.16	34378.2
.0011	40210.9	14.099	.7918	-39942959.8	2598.40	33239.6
.0011	39206.4	14.886	.8104	-37836121.4	2647.99	32169.2
.0011	38270.4	15.688	.8286	-35874977.8	2696.03	31159.4
.0011	37373.6	16.503	.8465	-34016710.2	2742.60	30205.8
.0012	36523.1	17.333	.8641	-32231274.3	2787.77	29305.0
.0012	35718.6	18.176	.8814	-30606694.1	2831.64	28453.8
.0012	34951.6	19.032	.8985	-29049746.5	2874.26	27644.8
.0012	34225.2	19.900	.9152	-27586372.1	2915.72	26877.0

.0011	34216.3	14.886	.8104	-37836121.4	2647.99	32169.2
.0011	34270.4	15.684	.8286	-35874977.8	2696.03	31159.4
.0011	37373.6	16.503	.8465	-34016718.2	2742.60	30205.8
.0012	36523.1	17.333	.8641	-32261274.3	2787.77	29305.0
.0012	35716.5	18.178	.8814	-30606694.1	2831.64	28453.8
.0012	34951.6	19.042	.8985	-29049746.5	2874.26	27648.8
.0012	34225.2	19.900	.9152	-27586372.1	2915.72	26887.0
.0013	33535.5	20.781	.9317	-26212013.9	2956.05	26165.7
.0013	32880.2	21.674	.9480	-24921858.7	2995.34	25482.1
.0013	32257.2	22.578	.9640	-23711010.3	3033.62	24833.7
.0013	31664.4	23.494	.9799	-22574981.6	3070.96	24218.2
.0014	31100.0	24.421	.9955	-21508658.8	3107.39	23633.4
.0014	30562.4	25.358	1.0109	-20507440.1	3142.97	23077.3
.0014	30049.8	26.306	1.0109	-45125915.0	3177.73	22548.0
.0014	29561.5	27.264	1.0109	-42079247.1	3210.98	21567.3
.0015	29096.5	28.233	1.0109	-39307761.8	3242.83	20658.7
.0015	28654.8	29.210	1.0109	-36781676.8	3273.38	19815.2
.0015	28235.3	30.198	1.0109	-34474815.8	3302.72	19030.6
.0015	27835.4	31.191	1.0109	-32364149.2	3330.93	18299.5
.0016	27454.1	32.195	1.0109	-30429391.5	3358.09	17617.0
.0016	27090.6	33.206	1.0109	-28652649.5	3384.26	16978.6
.0016	26743.2	34.225	1.0109	-27018116.0	3409.51	16380.7
.0016	26411.8	35.252	1.0109	-25511803.9	3433.90	15819.7
.0017	26096.0	36.285	1.0109	-24121315.8	3457.48	15292.5
.0017	25793.0	37.324	1.0109	-22835643.9	3480.29	14796.4
.0017	25502.1	38.373	1.0109	-21644997.4	3502.38	14328.9
.0017	25223.4	39.427	1.0109	-20540575.0	3523.79	13887.7
.0018	24956.4	40.488	1.0109	-19514094.1	3544.56	13470.7
.0018	24700.6	41.554	1.0109	-18559266.0	3564.72	13076.3
.0018	24455.6	42.626	1.0109	-17669837.6	3584.30	12702.7
.0018	24221.4	43.705	1.0109	-16840198.1	3603.34	12348.3
.0019	23996.8	44.788	1.0109	-16065304.5	3621.85	12011.9
.0019	23781.2	45.878	1.0109	-15340616.5	3639.88	11692.1
.0019	23577.7	46.972	1.0109	-14662039.4	3657.43	11387.9
.0019	23381.1	48.072	1.0109	-14025874.4	3674.54	11098.2
.0020	23190.5	49.177	1.0109	-13428774.7	3691.23	10821.9
.0020	23024.8	50.287	1.0109	-12867707.7	3707.50	10558.3
.0020	22853.1	51.401	1.0109	-12339921.0	3723.39	10306.6
.0020	22694.6	52.521	1.0109	-11842912.5	3738.91	10065.9
.0021	22539.5	53.645	1.0109	-11374404.7	3754.07	9835.6
.0021	22414.2	54.773	1.0109	-10932321.5	3768.90	9615.2
.0021	22240.8	55.906	1.0109	-10514767.4	3783.40	9403.9
.0021	22107.0	57.043	1.0109	-10120009.8	3797.58	9201.3
.0022	21975.0	58.184	1.0109	-9746462.7	3811.47	9006.8
.0022	21841.3	59.330	1.0109	-9392072.2	3825.06	8820.0
.0022	21716.5	60.479	1.0109	-9057304.3	3838.38	8640.5
.0022	21590.1	61.633	1.0109	-8739133.1	3851.44	8467.9
.0023	21461.6	62.790	1.0109	-8437030.6	3864.24	8301.8
.0023	21340.7	63.951	1.0109	-8149958.1	3876.79	8141.8
.0023	21226.9	65.116	1.0109	-7876957.4	3889.10	7987.7
.0023	21090.0	66.285	1.0109	-7617144.3	3901.19	7839.0
.0024	20999.6	67.457	1.0109	-7369701.3	3913.05	7695.7
.0024	20715.3	68.633	1.0109	-7133872.1	3924.70	7557.3
.0024	20537.0	69.812	1.0109	-6908956.3	3936.15	7423.6

PIEZOMETRIC PRESSURE IS 21734.75

MUZZLE VELOCITY IS 3928.3 FEET PER SECOND

PIEZOMETRIC EFFICIENCY IS 33.4 PERCENT

CORRECTED PIEZOMETRIC EFFICIENCY IS 37.9 PERCENT

BALLISTIC EFFICIENCY IS 34.7 PERCENT

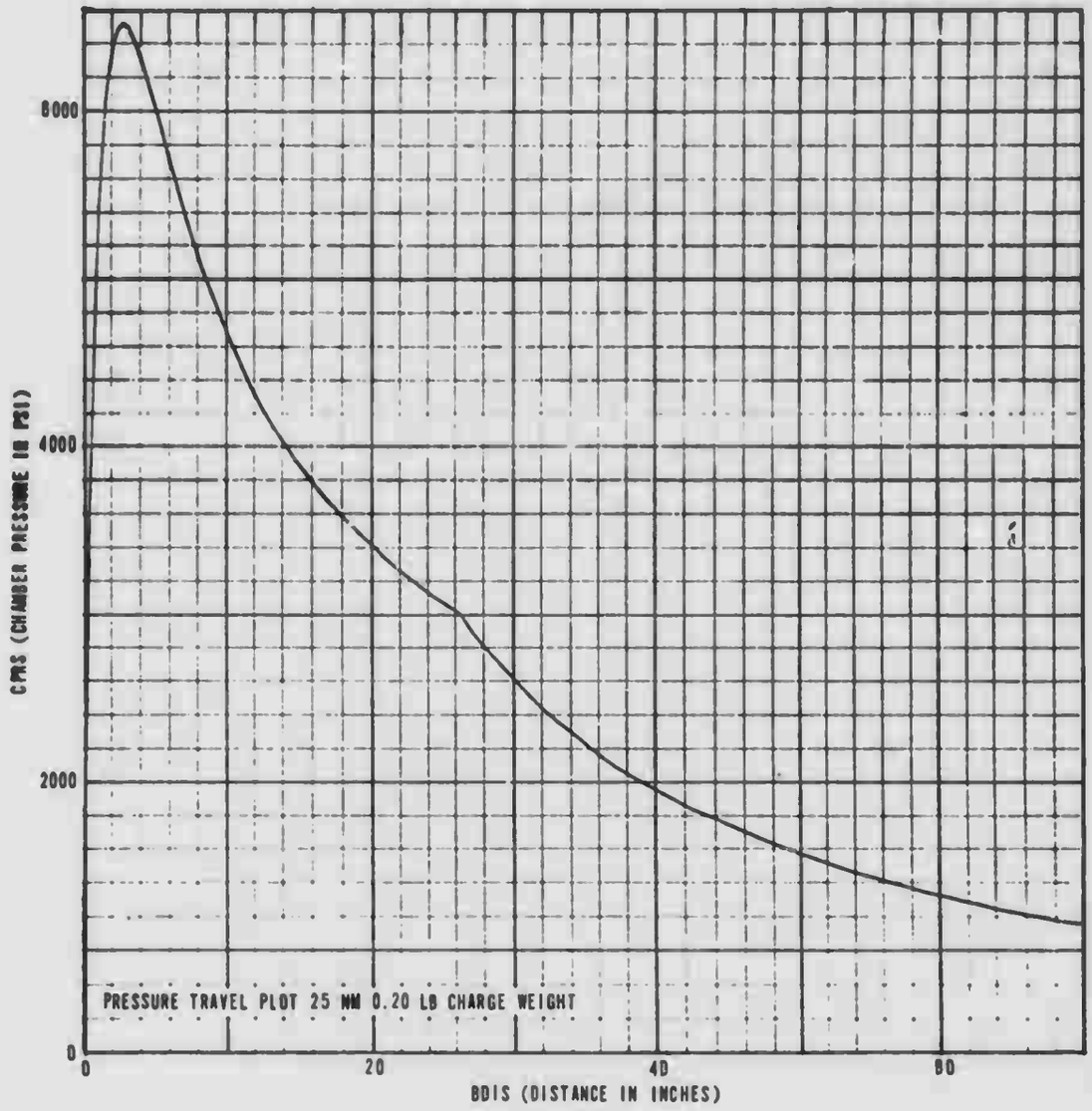


Figure 5. Graph of 20mm Performance 0.015 Web.

 (The reverse of this page is blank.)

TABLE III. COMPUTER PRINTOUT OF 20MM PERFORMANCE 0.020 WEB.

SHOT WT.	CHARGE	WEB	H.LENGTH	CHB VOL HOLE AREA	
.40	.140	.0220	69.0	5.74	.76

PROPELLANT USED IN DEVICE IS M-10

TIME	CHAMB PRES	TRAVEL	PROP BURNED	PRES SLOPE	VELOCITY	BS PRES
.0000	4000.0	.001	.0027	29640546.3	6.17	4000.0
.0000	4741.0	.004	.0059	34139304.6	13.48	4741.0
.0001	5594.5	.009	.0095	39557022.5	22.10	5594.5
.0001	6583.3	.017	.0138	45665753.5	32.25	6583.3
.0001	7720.1	.029	.0186	51788485.4	44.15	7719.8
.0001	9014.3	.044	.0242	59074131.1	58.05	9014.3
.0002	10491.6	.064	.0305	66498321.2	74.22	10490.6
.0002	12154.1	.089	.0376	72872565.5	92.95	12152.1
.0002	13975.9	.120	.0455	79411508.7	114.49	13972.3
.0002	15961.2	.156	.0542	85970003.4	139.09	15954.9
.0003	18110.4	.200	.0638	92360045.9	167.00	18100.0
.0003	20419.6	.249	.0745	98556820.7	198.45	20402.4
.0003	22883.6	.304	.0863	105099001.4	233.69	22856.6
.0003	25510.6	.400	.0994	110832946.5	272.95	25469.2
.0004	28281.7	.468	.1138	115404895.7	316.45	28218.7
.0004	31186.4	.590	.1294	117065760.1	364.36	31073.5
.0004	34093.6	.707	.1461	114717553.1	416.71	33958.3
.0004	36961.6	.841	.1639	110128894.6	473.40	36769.9
.0005	39716.6	.992	.1827	103277387.3	534.21	39449.3
.0005	42296.5	1.162	.2022	92795849.9	598.86	41937.1
.0005	44616.6	1.352	.2224	80477086.9	666.91	44140.6
.0005	46628.3	1.563	.2433	66976117.0	737.85	46012.5
.0006	48302.7	1.795	.2646	52837290.0	811.11	47523.3
.0006	49623.7	2.050	.2863	38021883.1	886.13	48657.9
.0006	50589.2	2.327	.3083	24854665.1	962.31	49410.8
.0006	51210.6	2.627	.3305	11979920.5	1039.11	49814.5
.0007	51510.1	2.950	.3527	333017.8	1116.00	49877.2
.0007	51518.6	3.297	.3750	-9870462.7	1192.53	49640.2
.0007	51271.7	3.666	.3972	-18529847.0	1268.29	49143.9
.0007	50808.6	4.057	.4192	-25643059.6	1342.95	48431.6
.0008	50167.3	4.471	.4411	-31284109.7	1416.25	47544.8
.0008	49345.2	4.907	.4627	-35579106.8	1487.98	46524.6
.0008	48495.8	5.366	.4841	-38686249.1	1557.98	45406.0
.0008	47528.6	5.841	.5052	-40761914.1	1626.15	44221.3
.0009	46509.8	6.339	.5260	-41986575.6	1692.44	42997.1
.0009	45460.0	6.857	.5465	-42509956.2	1756.81	41755.5
.0009	44397.2	7.393	.5666	-42478766.8	1819.27	40513.9
.0009	43335.3	7.948	.5865	-42013647.6	1879.83	39288.3
.0010	42294.9	8.521	.6060	-41218803.8	1938.54	38083.1
.0010	41284.5	9.111	.6252	-40180924.8	1995.45	36911.9
.0010	40309.9	9.718	.6442	-38970827.1	2050.60	35778.0
.0010	39375.7	10.341	.6628	-37809060.2	2104.08	34685.2
.0011	38480.6	10.980	.6810	-36602359.1	2155.93	33631.7
.0011	37615.6	11.634	.6990	-35328732.6	2206.21	32618.3
.0011	36782.2	12.303	.7166	-34019064.8	2255.00	31645.7
.0011	35981.7	12.987	.7339	-32697370.3	2302.35	30714.1
.0012	35206.2	13.685	.7509	-31382032.2	2348.32	29823.1
.0012	34459.7	14.394	.7676	-30086870.3	2392.99	28971.8
.0012	33737.6	15.120	.7840	-28822040.7	2436.40	28159.2
.0012	33037.0	15.857	.8002	-27594785.8	2478.62	27383.9
.0013	32357.1	16.607	.8161	-26410050.2	2519.69	26644.4
.0013	31696.9	17.369	.8318	-25269548.5	2559.68	25939.1
.0013	31055.1	18.143	.8472	-24175267.3	2598.63	25266.6
.0013	30430.7	18.928	.8625	-23129531.4	2636.60	24625.1

(The

.0012	34804.2	13.685	.7509	-3138[illegible]	[illegible]	[illegible]
.0012	34074.7	14.396	.7676	-30086870.3	2392.99	28971.8
.0012	33327.5	15.120	.7840	-28822040.7	2436.40	28154.2
.0012	32637.0	15.857	.8002	-27594785.8	2478.62	27383.9
.0013	31917.1	16.607	.8161	-26410050.2	2519.69	26644.4
.0013	31256.9	17.369	.8318	-25269548.5	2559.68	25939.1
.0013	30625.1	18.143	.8472	-24175207.3	2598.63	25266.6
.0013	30020.7	18.928	.8625	-23124531.4	2636.60	24625.1
.0014	29442.5	19.725	.8774	-22252694.4	2673.62	24013.3
.0014	28886.2	20.532	.8921	-21411411.8	2709.73	23426.9
.0014	28350.9	21.350	.9066	-20601758.3	2744.98	22865.0
.0014	27835.8	22.179	.9208	-19824036.6	2779.40	22326.3
.0015	27340.2	23.018	.9347	-19078141.0	2813.03	21809.8
.0015	26863.3	23.867	.9485	-18363653.9	2845.89	21314.4
.0015	26404.2	24.726	.9620	-17679923.4	2878.01	20839.2
.0015	25962.2	25.593	.9753	-17026125.4	2909.44	20383.2
.0016	25536.5	26.471	.9884	-16401314.0	2940.18	19945.4
.0016	25126.5	27.357	1.0013	-15804460.4	2970.28	19524.9
.0016	24731.4	28.253	1.0013	-32581343.4	2999.76	19120.9
.0016	23916.9	29.157	1.0013	-30691354.3	3028.13	18398.9
.0017	23149.6	30.070	1.0013	-28946863.2	3055.45	17722.5
.0017	22425.9	30.990	1.0013	-27334430.7	3081.79	17087.7
.0017	21742.6	31.919	1.0013	-25842146.4	3107.22	16491.3
.0017	21096.5	32.856	1.0013	-24459286.1	3131.77	15930.2
.0018	20485.0	33.798	1.0013	-23176143.6	3155.52	15401.6
.0018	19905.6	34.748	1.0013	-21984169.9	3178.49	14903.0
.0018	19356.0	35.705	1.0013	-20875373.2	3200.74	14432.1
.0018	18834.1	36.668	1.0013	-19842728.6	3222.31	13986.9
.0019	18338.1	37.638	1.0013	-18879847.6	3243.22	13565.5
.0019	17866.1	38.614	1.0013	-17980956.0	3263.52	13166.1
.0019	17416.5	39.596	1.0013	-17140829.4	3283.23	12787.2
.0019	16988.0	40.584	1.0013	-16354735.5	3302.39	12427.4
.0020	16579.1	41.577	1.0013	-15618383.5	3321.02	12085.4
.0020	16188.7	42.576	1.0013	-14927878.1	3339.15	11759.9
.0020	15815.5	43.581	1.0013	-14279679.3	3356.80	11450.0
.0020	15458.5	44.590	1.0013	-13670505.8	3374.00	11154.5
.0021	15116.7	45.605	1.0013	-13097603.5	3390.76	10872.6
.0021	14789.3	46.625	1.0013	-12558116.2	3407.11	10603.4
.0021	14475.3	47.649	1.0013	-12049660.5	3423.06	10346.0
.0021	14174.1	48.678	1.0013	-11570002.6	3438.63	10099.9
.0022	13884.6	49.712	1.0013	-11117098.5	3453.83	9864.3
.0022	13606.9	50.751	1.0013	-10689075.2	3468.69	9638.6
.0022	13339.7	51.793	1.0013	-10284214.7	3483.22	9422.2
.0022	13082.6	52.841	1.0013	-9900939.6	3497.42	9214.6
.0023	12835.1	53.892	1.0013	-9537799.6	3511.32	9015.3
.0023	12596.6	54.947	1.0013	-9193312.7	3524.93	8823.8
.0023	12366.8	56.007	1.0013	-8866382.2	3538.25	8639.8
.0023	12145.1	57.070	1.0013	-8555907.7	3551.29	8462.7
.0024	11931.2	58.137	1.0013	-8260840.5	3564.08	8292.3
.0024	11724.7	59.208	1.0013	-7980211.6	3576.61	8128.2
.0024	11525.2	60.283	1.0013	-7713125.1	3588.89	7970.0
.0024	11332.4	61.362	1.0013	-7458750.9	3600.95	7817.5
.0025	11145.9	62.444	1.0013	-7216320.0	3612.77	7670.4
.0025	10965.5	63.530	1.0013	-6985119.2	3624.38	7528.4
.0025	10790.9	64.619	1.0013	-6754486.1	3635.77	7391.3
.0025	10621.8	65.711	1.0013	-6553805.3	3646.96	7258.8
.0026	10457.9	66.807	1.0013	-6352504.3	3657.96	7130.7
.0026	10299.1	67.906	1.0013	-6160050.2	3668.76	7006.8
.0026	10145.1	69.008	1.0013	-5975946.2	3679.37	6886.9

PIEZOMETRIC PRESSURE IS 19071.38

MUZZLE VELOCITY IS 3679.3 FEET PER SECOND

PIEZOMETRIC EFFICIENCY IS 47.0 PERCENT

CORRECTED PIEZOMETRIC EFFICIENCY IS 41.7 PERCENT

BALLISTIC EFFICIENCY IS 33.8 PERCENT

(The reverse of this page is blank.)

B

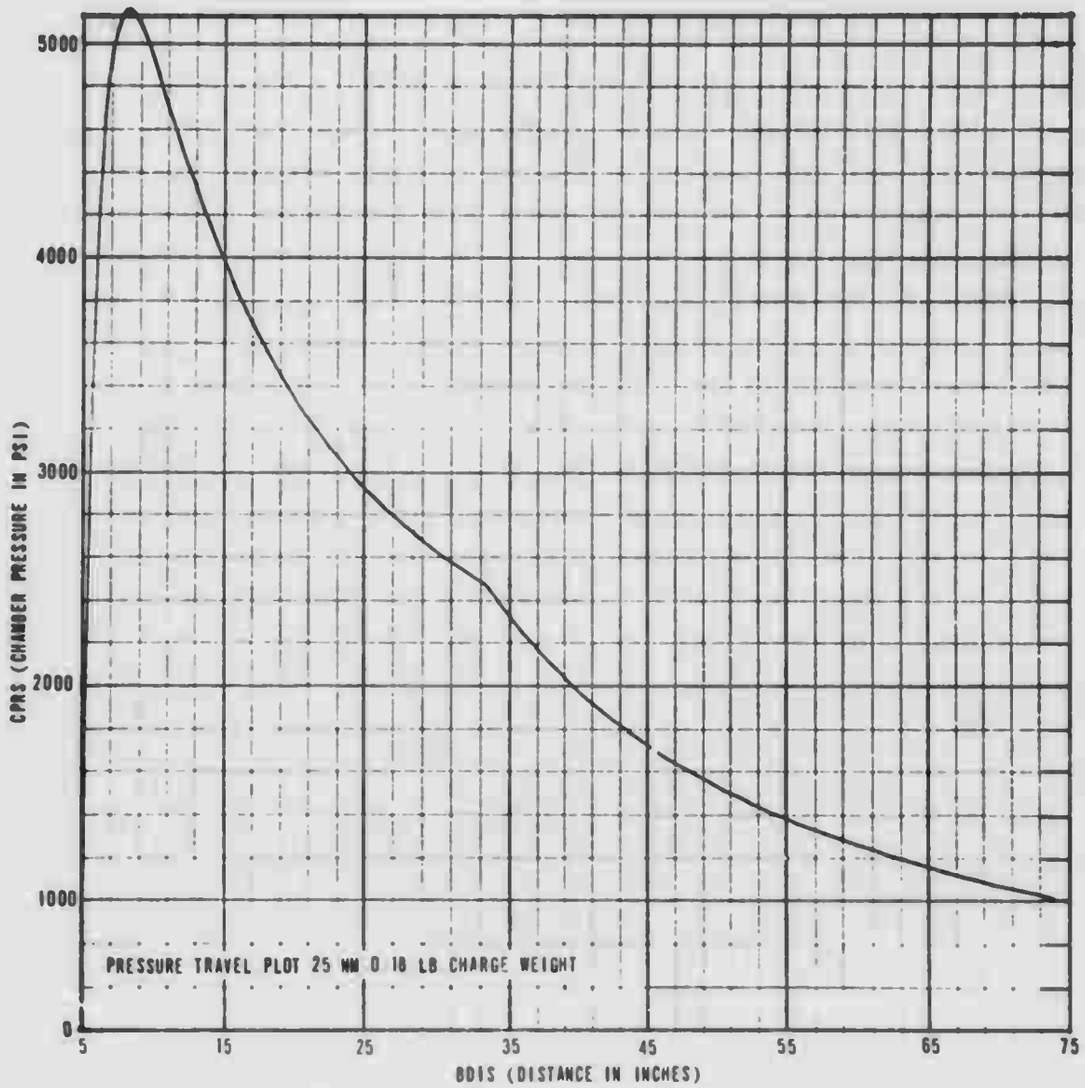


Figure 6. Graph of 20mm Performance 0.020 Web.

TABLE IV. INTERIOR BALLISTIC PROGRAM FORTRAN 4 LISTING.

```
PROGRAM      P095R       FORTRAN EXTENDED V 1.0                  28/03/69          15.19.47.

                PROGRAM P095R(INPUT,OUTPUT,TAPE5=INPUT,TAPE6=OUTPUT,FILMPL)          P095800 00001
          $JOB            F99 SADLER, J   11102543V1 R958-2 095AG1 00109    9      P0958   00003
          $0  O/P RQ  PLOT                                                         P0958   00004
          $EXECUTE        IMJOM                                                    P0958   00005
    05    $IAJOM          MAP                                                      P0958   00006
          $IRETC 95R                                                               P0958   00007
                COMMON/   /PCPRS(1000),PHUIS(1000),RUN,PTOP,NPTS                   P0958   00008
                DIMENSION PSY(20),VEE(20)                                          P0958   00009
                DIMENSION PRS(20),RATE(20),TYPE(8)                                 P0958   00010
    10          READ(5,3)FIMP,GAMA,RHO,CVL,(TYPE(N),N=1,4)                         P0958   00011
              3 FORMAT(F8.1,F8.3,F8.4,F8.2,4A2)                                    P0958   00012
                READ(5,4)PRS                                                       P0958   00013
              4 FORMAT(10F8.1)                                                     P0958   00014
                READ(5,5)RATE                                                      P0958   00015
    15        5 FORMAT(10F8.3)                                                     P0958   00016
                READ(5,24)VEE                                                      P0958   00017
             24 FORMAT(10F8.1)                                                     P0958   00018
                READ(5,25)PSY                                                      P0958   00019
             25 FORMAT(10F8.3)                                                     P0958   00020
    20          PIT=1.5                                                          P0958   00021
                TAD=GAMA/(GAMA-1.)                                                 P0958   00022
              6 READ(5,7)AREA,CVOL,SHOT,RUN,WEB,BETA,CHG,SCPRS                     P0958   00023
              7 FORMAT(F7.3,F7.3,F7.3,F7.1,F7.4,F7.2,F7.3,F8.1)                    P0958   00024
                NPTS=0                                                           P0958   00025
    25          HP=0.                                                            P0958   00026
                VEL=0.                                                           P0958   00027
                WARE=2.*CHG/(RHO*WEB)                                            P0958   00028
                WRITE(6,8)                                                       P0958   00029
              8 FORMAT(1H1,61H  SHOT WT.     CHARGE       WEB     B.LENGTH    CHB VOL  P0958   00030
    30       1BOWF AREA//)                                                       P0958   00031
                WRITE(6,9)SHOT,CHG,WEB,RUN,CVOL,AREA                             P0958   00032
              9 FORMAT(F10.2,F10.3,F10.4,F10.1,F10.2,F10.2///)                    P0958   00033
                WRITE(6,35)(TYPE(N),N=1,4)                                       P0958   00034
             35 FORMAT(32H  PROPELLANT USED IN DEVICE IS  ,4A2,///)               P0958   00035
    35          WRITE(6,27)                                                      P0958   00036
             27 FORMAT(101H            TIME        CHAMB PRES        TRAVEL        PRO P0958   00037
               1P BURNED   PRES SLOPE        VELOCITY   BS PRES//)                P0958   00038
                HP=0.0                                                           P0958   00039
                VEL2=0.                                                          P0958   00040
```

```
40          BDTS=0.0                                                          P0958   00041
            PTOP=3000.                                                        P0958   00042
            CPRS=SCPRS                                                        P0958   00043
            GAMH=(1.+BETA)*(GAMA-1.)                                          P0958   00044
            DO 39 J=1,750,I                                                   P0958   00045
45        74 JA=1                                                           P0958   00046
          78 IF(CPRS-PRS(JA))77,76,75                                         P0958   00047
          75 JA=JA+1                                                          P0958   00048
             GO TO 78                                                         P0958   00049
          76 R=RATE(JA)                                                       P0958   00050
50           GO TO 10                                                         P0958   00051
          77 DIT=PRS(JA)-PRS(JA-1)                                            P0958   00052
             DAT=RATE(JA)-RATE(JA-1)                                          P0958   00053
             PIC=CPRS-PRS(JA-1)                                               P0958   00054
             DIM=((PIC/DIT)*DAT)                                              P0958   00055
55           R=RATE(JA-1)+DIM                                                 P0958   00056
          10 IF (RP-CHG)11,80,80                                              P0958   00057
          80 DNDT=0                                                           P0958   00058
             GO TO 12                                                         P0958   00059
          11 DNDT=R*RHO*RARE                                                  P0958   00060
60           RP=RP+(DNDT*.000025)                                             P0958   00061
          12 VEL1=VEL2                                                        P0958   00062
             RTM=(VEL2*VEL2)/(GAMA*32.17*FIMP*PIT)                            P0958   00063
             ROOT=1./(1.+(((GAMA-1.)/2.)*RTM))                                P0958   00064
             TUT=ROOT**TAD                                                    P0958   00065
65           PREX=CPRS*TUT                                                    P0958   00066
             KO=1                                                             P0958   00067
          50 IF(VEE(KO)-VEL2)51,52,53                                         P0958   00068
          51 KO=KO+1                                                          P0958   00069
             GO TO 50                                                         P0958   00070
70        52 PFAC=PSY(KO)                                                     P0958   00071
             GO TO 59                                                         P0958   00072
          53 RAG=(VEL2-VEE(KO-1))/(VEE(KO)-VEE(KO-1))                         P0958   00073
             PFAC=((PSY(KO)-PSY(KO-1))*RAG)+PSY(KO-1)                         P0958   00074
          59 EFM=(SHOT+(CHG/PFAC))/32.17                                      P0958   00075
75           ACEL=PREX*AREA*32.17/SHOT                                        P0958   00076
             VEL2=VEL1+(ACEL*.000025)                                         P0958   00077
             ACOL=(ACEL*.000025)/2.                                           P0958   00078
             RINC=(VEL1*.000025)+(ACOL*.000025)                               P0958   00079
             BDTS=BDIS+(RINC*12.)                                             P0958   00080
80        13 AVOL=CVOL+(BDIS*AREA)                                            P0958   00081
             DLDT=VEL2                                                        P0958   00082
             URW=(CHG-RP)/RHO                                                 P0958   00083
             COVL=CVL*RP                                                      P0958   00084
             DPDT=((DNDT*FIMP*12.)-((GAMH*EFM*ACEL*VEL2*12.)+(AREA*PREX*VEL1*12 P0958   00085
85           1.)))/(AVOL-(URW+COVL))                                          P0958   00086
             DOPE=J                                                           P0958   00087
             TIME=DOPE*.000025                                                P0958   00088
             FPU=RP/CHG                                                       P0958   00089
             IF(CPRS.GT.PTOP) PTOP=CPRS                                       P0958   00090
90        15 WRITE(6,17)TIME,CPRS,BDIS,FPU,DPDT,DLDT,PREX                     P0958   00091
```

```
                                                                                P0958   00090
   90                   15 WRITE(6,17)TIME,CPRS,BDIS,FPU,DPDT,DLDT,PREX         P0958   00091
                        17 FORMAT(F15.4,F15.1,F15.3,F15.4,F15.1,F15.2,F10.1)     P0958   00092
                           NPTS=NPTS+1                                          P0958   00093
                           PCPRS(NPTS)=CPRS                                     P0958   00094
                           PBDIS(NPTS)=BDIS                                     P0958   00095
   95                      CPRS=CPRS+(DPDT*.000025)                             P0958   00096
                           IF(BDIS.GE.RUN) GO TO 79                             P0958   00097
                        39 CONTINUE                                             P0958   00098
                        79 DELV=VEL2-VEL1                                       P0958   00099
                           ORUN=BDIS-RUN                                        P0958   00100
  100                      ADV=(1.-(ORUN/(RINC*12.)))*DELV                      P0958   00101
                           VM=VEL1+ADV                                          P0958   00102
                           AO=(VM*VM/RUN)*SHOT*12./(AREA*64.4)                  P0958   00103
                           WRITE(6,40)AO                                        P0958   00104
                        40 FORMAT(//25H PIEZOMETRIC PRESSURE IS ,F9.2,//)       P0958   00105
  105                      WRITE(6,41)VM                                        P0958   00106
                        41 FORMAT(/19H MUZZLE VELOCITY IS,F8.1,16H FEET PER SECOND/)  P0958   00107
                           AR=AO/PTOP                                           P0958   00108
                           AF=AR*100.                                           P0958   00109
                           WRITE(6,42)AF                                        P0958   00110
  110                      FORMAT(//26H PIEZOMETRIC EFFICIENCY IS,F7.1,8H PERCENT)  P0958   00111
                           AR=(AF*EFM*32.17)/SHOT                               P0958   00112
                           FKE=(VM*VM*SHOT)/(2.*32.17)                          P0958   00113
                           TE=CHG*FIMP/(GAMA-1.)                                P0958   00114
                           BE=FKE/TE*100.                                       P0958   00115
  115                      WRITE(6,44)AR                                        P0958   00116
                        44 FORMAT(//36H CORRECTED PIEZOMETRIC EFFICIENCY IS,F7.1,8H PERCENT)  P0958   00117
                           WRITE(6,43)BE                                        P0958   00118
                        43 FORMAT(//24H BALLISTIC EFFICIENCY IS,F8.1,8H PERCENT)  P0958   00119
                           CALL RPLOT                                           P0958   00120
  120                      GO TO 6                                              P0958   00121
                           END                                                  P0958   00122
                     $IBFTC RPLOT                                               P0958   00123
                           SUBROUTINE RPLOT                                     P0958   00124
                           COMMON/    /PCPRS(1000),PBDIS(1000),RUN,PTOP,NPTS    P0958   00125
                           I=0                                                  P0958   00126
   05                      XL=PBDIS(1)                                          P0958   00127
                           XR=PBDIS(NPTS)                                       P0958   00128
                           YB=PCPRS(1)                                          P0958   00129
                           YT=PTOP                                              P0958   00130
                           CALL DXDYV(1,XL,XR,DX,N,I,NX,20.0,IERR)              P0958   00131
   10                      CALL DXDYV(2,YB,YT,DY,M,J,NY,20.0,IERR)              P0958   00132
                           I=-1                                                 P0958   00133
                           J=-J                                                 P0958   00134
                           CALL GRIDIV(L,XL,XR,YB,YT,DX,DY,N,M,I,J,NX,NY)       P0958   00135
                           CALL PRINTV(-4,4HBDIS,500,10)                        P0958   00136
   15                      CALL APRNTV(0,-14,-4,4HCPRS,10,500)                  P0958   00137
                     C     CALL APLOTV(NPTS,PT(1),PR1(1),1,1,1,55,IERR)         P0958   00138
                     C     CALL APLOTV(NPTS,PT(1),PR2(1),1,1,1,38,IERR)         P0958   00139
                           IX1=NXV(PBDIS(1))                                    P0958   00140
                           IY1=NYV(PCPRS(1))                                    P0958   00141
   20                      DO 300 IKK=2,NPTS                                    P0958   00142
                           IX2=NXV(PBDIS(IKK))                                  P0958   00143
                           IY2=NYV(PCPRS(IKK))                                  P0958   00144
                           CALL LINEV(IX1,IY1,IX2,IY2)                          P0958   00145
                           IX1=IX2                                              P0958   00146
   25                      IY1=IY2                                              P0958   00147
                      300  CONTINUE                                             P0958   00148
                           RETURN                                               P0958   00149
                           END                                                  P0958   00150
```

(The reverse of this page is blank.)

SECTION IV

EXPERIMENTAL RESULTS

NORMAL DEFLAGRATION

The validity of the preceding analysis is easily assessed by measuring the pressure-time history and muzzle velocity of a given device and correlating the results with those predicted by the theory. This experimental effort was conducted at the Jet Propulsion Laboratory of the California Institute of Technology under NASA sponsorship. The device which was used for this purpose is shown in Figure 7.

Figure 7. Device to Measure Pressure-Time History and Muzzle Velocity.

Pressures were measured in the chamber and at two additional points down the barrel by means of high-pressure Kistler piezometric pressure transducers feeding Kistler charge amplifiers and recorded on persistent phosphor Techtronix oscilloscopes. Muzzle velocities were measured by means of break screens connected to Hewlett-Packard digital clocks.

The launch tube was of smooth bore configuration and for maximum flexibility was constructed with a uniform bore diameter rather than with an expanded chamber; this design allows an infinitely variable chamber volume. Ignition and propellant loading techniques are shown in Figure 8.

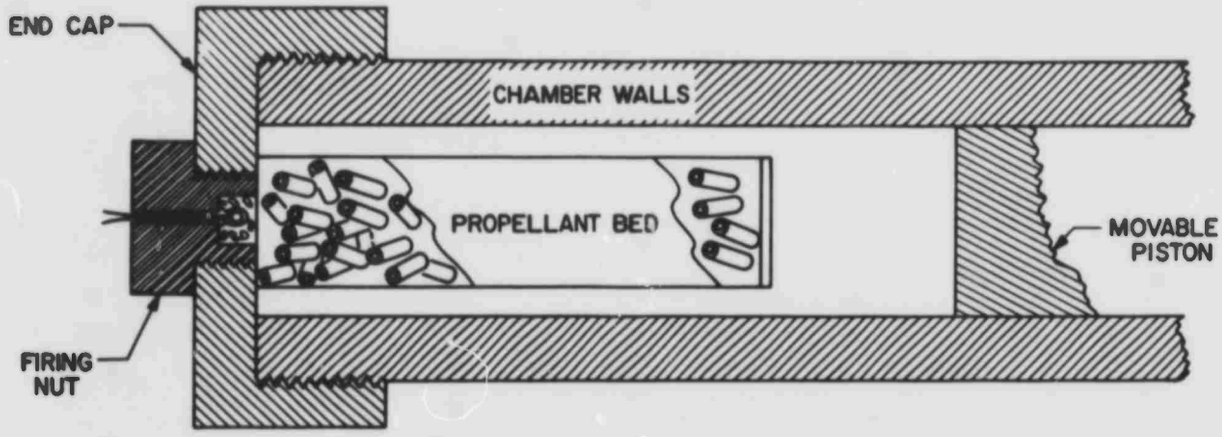


Figure 8. Ignition and Propellant Loading Techniques.

The initial chamber volume is determined by the location of the piston base while the loading volume is a function of the diameter and length of the phenolic sleeve into which the propellant is initially packed. The ignitor used consists of a firing nut containing an Atlas electric match surrounded by 300 mg of black powder. This type igniter gives a short-duration flame of high intensity with little brisance. When the tubular propellant grains are not too tightly packed, the effect of the phenolic loading sleeve may be neglected except insofar as the volume it displaces is concerned.

Firings demonstrating proper deflagration and typical correlation with the above referenced theory are illustrated in Figures 9, 10, and

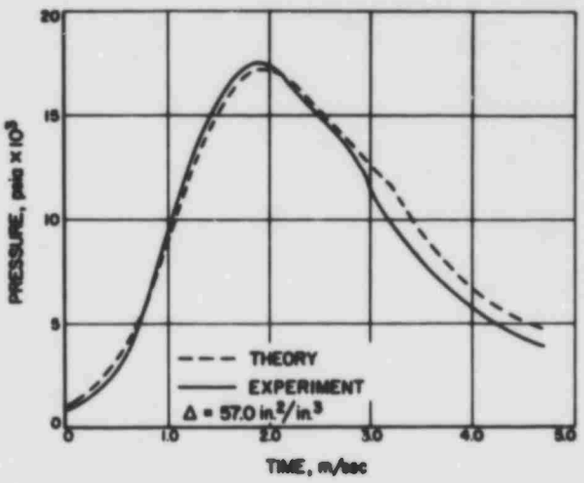


Figure 9. Pressure Time Plot With $\Delta = 57.0$ in.^{2}/in.^{3}.

11. A qualitative delineation of the phenomena occurring in Figure 9, for example, would be as follows:

1. t = 0 to t = 1.0 m/sec: Very slow increase in chamber volume as the result of an almost negligible projectile velocity, hence very rapid pressure increase due to energy release by propellant in almost constant chamber volume.

2. t = 1.0 m/sec to t = 1.9 m/sec: Projectile velocity increasing and, thus, exposed chamber volume increasing more rapidly. Excess energy input decreasing as function of incremental volume to be pressurized.

3. Peak pressure (t = 1.9) to propellant burnout (t = 2.9 experimentally, 3.2 analytically): Plenum volume increasing more rapidly than energy input. Sharp break in curve slope due to propellant burnout.

4. Subsequent to burnout, a very rapid pressure decrease occurs as a result of the expansion of the gases, heat loss to tube, and further energy imparted to projectile.

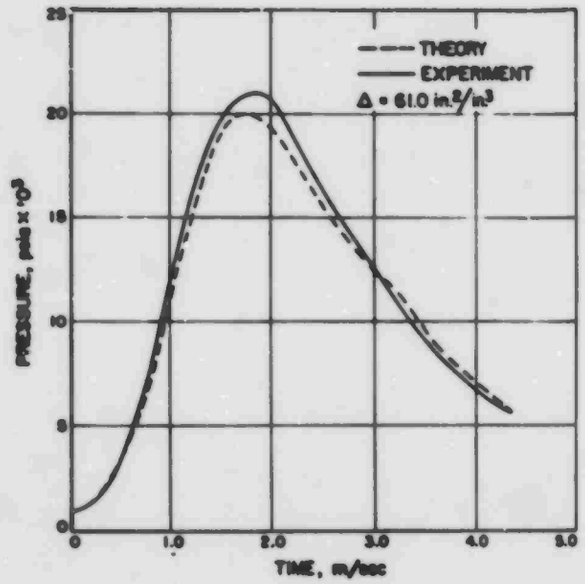


Figure 10. Pressure Time Plot With $\Delta = 61.0$ in.^{2}/in.^{3}.

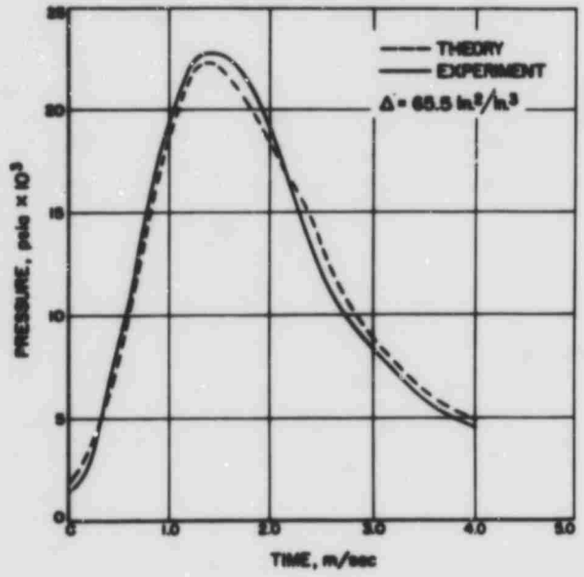


Figure 11. Pressure Time Plot With $\Delta = 65.5$ in.^{2}/in.^{3}.

In these three firings, the primary difference exhibited between the experimental data and the analysis is a result of the following factor: the single-perforate propellant is assumed to burn externally and internally in a radial manner until the total charge is consumed.

In reality, this does not occur. A certain fraction of the grains fragment during combustion, and this increases the exposed burning surface and, in general, leads to slightly higher peak pressures and somewhat earlier web burnout than is analytically predicted. The difference, typically, is of only a few percent in peak pressure and is of such a nature that there is no way to express it analytically.

Figures 9, 10, and 11 show the quite good correlation between theory and experiment which is attainable when the density of loading Δ is kept at less than 75 $in.^2/in.^3$. At loadings above this level, a different mechanism of combustion becomes manifest and could probably be best described as a transition through shock-driven deflagration to virtual charge detonation. The charge characteristics are presented in Table V.

TABLE V. CHARGE CHARACTERISTICS.

Plot References	Charge Weight (gm)	Propellant Web (in.)	Slug Weight (gm)	Δ ($in.^2/in.^3$)	Muzzle Velocity (fps)	
					Predicted	Actual
Figure 9	86.2	0.0164	560	57.0	2,080	2,040
Figure 10	90.0	0.0164	560	61.0	2,220	2,210
Figure 11	110.0	0.0190	508	65.5	2,360	2,300
Figure 12	97.5	0.0164	560	76.7	2,250	2,150
Figure 13	93.0	0.0164	550	80.0	2,190	2,220
Figure 14	105.0	0.0164	560	82.0	2,350	2,700

SHOCK-DRIVEN DEFLAGRATION

It was mentioned previously that the phenolic tube had no effect on the interior ballistic solution. This is not true, however, if the propellant is packed too tightly into the tube. The propellant used was M-10, which is virtually 100 percent nitrocellulose with no nitroglycerine

loading and, hence, would be expected to be relatively insensitive to detonation characteristics.

Figures 12, 13, and 14 show this phenomenon of transition from weak shock-driven deflagration to strongly shock-driven deflagration. Figure 15 shows the remains of an end cap when loading was increased to the point where a response similar to complete detonation occurred. No pressure record is available for this firing because the breech pressure transducer was also destroyed. An indirect method of pressure determination may be made by the calculation of the force necessary to shear the normalized 4130 end cap and indicates a peak pressure of at least 450,000 psig.

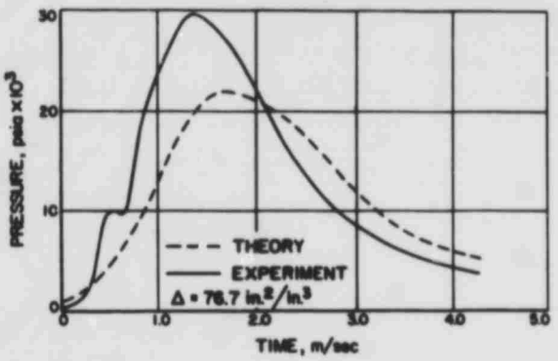


Figure 12. Pressure Time Plot With $\Delta = 76.7$ in.^{2}/in.^{3}.

From the illustrated firings, it is possible to characterize the combustion of the propellant into various regimes as a function of the burning surface per unit of free initial volume. Symbolically, this would be

$$\Delta = S_B/V_{IF}$$

as

$$S_B = 2\, C_w/\rho_p\, w_o$$

then

$$V_{IF} = L\, A_p - C_w/\rho_p$$

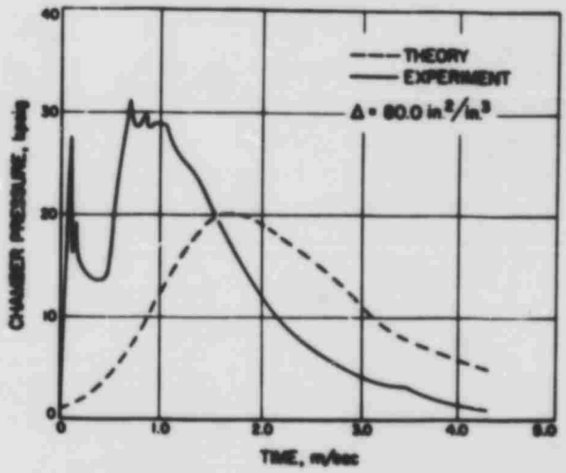


Figure 13. Pressure Time Plot With Δ = 80.0 in.^{2}/in.^{3}.

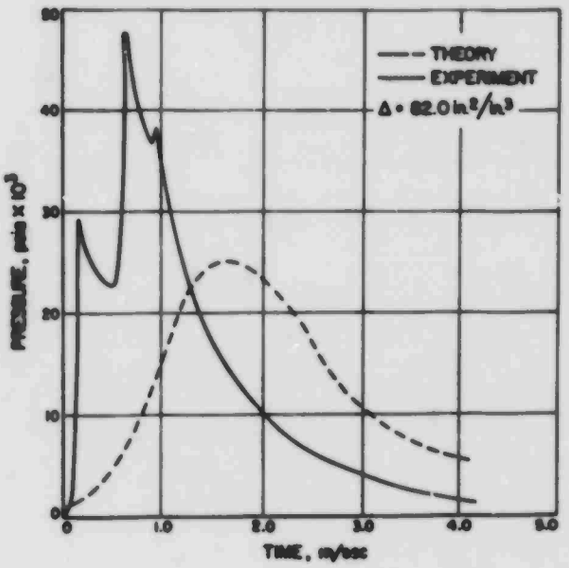


Figure 14. Pressure Time Plot With Δ = 82.0 in.^{2}/in.^{3}.

It was mentioned earlier that, for proper deflagration in this system, Δ must be less than 75 in.^{2}/in.^{3}. In Figure 12, Δ = 76.7 in.^{2}/in.^{3} and it was seen that a slight pressure pulse occurs, then damps out, but drives the peak pressure to a value approximately 30 percent higher than what would have been encountered during proper deflagration.

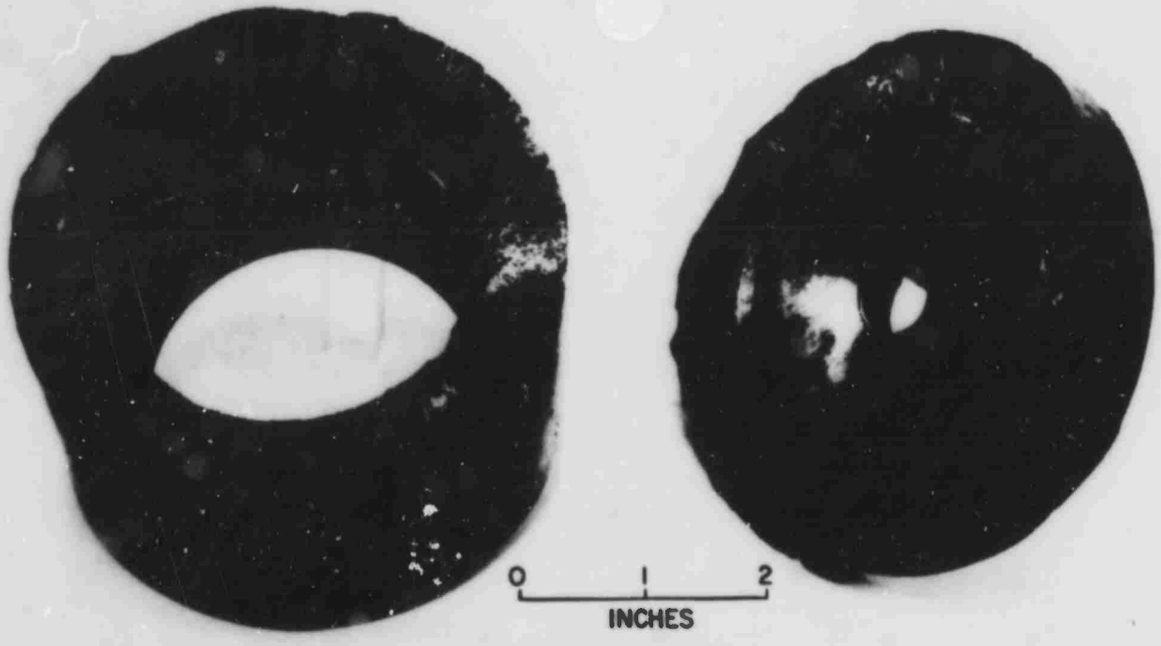


Figure 15. End Cap After Detonative Reaction.

In Figure 13, for which $\Delta = 80$ in.^{2}/in.^{3}, the initial pressure spike is rapid and narrow and quickly decays to be followed by another broader pressure pulse to approximately the same value. Figure 14 shows the pressure-time profile of a loading with a $\Delta = 82$ in.^{2}/in.^{3}.

The initial pressure wave is virtually identical to that exhibited by the previous loading. The second spike, however, is much higher and gives a peak pressure almost 100 percent higher than would be expected if linear regression were the only mechanism at work.

The loading represented by the wreckage shown in Figure 15 was $\Delta = 86.5$ in.^{2}/in.^{3}. A detonation-like reaction phenomenon had occurred, resulting in a pressure probably well above the 450,000 psig mentioned previously. The response could have been a true detonation of the individual propellant grains, which then formed a gaseous blast over-pressure wave to act on the restraining steel. The energy release rate was such that this is the most likely mode of reaction.

The Δ values given for the onset of this highly undesirable mode of reaction would include most fully loaded cartridge cases with thin web propellant. This demonstrates the requirements for either deterring or inhibiting a large fraction of the initial surface area. Good ballistic design, however, requires a tradeoff between reproducible ignition and the formation of these dangerous shock waves in the deflagrating propellant bed.

From the previous results for the system under consideration, the following regimes can be defined:

$\Delta < 75$	Proper deflagration
$75 < \Delta < 86$	Shock-driven deflagration
$\Delta > 86$	Detonation like response

These particular Δ values are doubtless a function of propellant composition and ignition technique. They do graphically demonstrate, however, that the ballistic designer must be cautious when approaching very high loading densities to be certain that the regimes, other than normal propellant regression, are avoided.

REFERENCES

1. Heiney, O.K., "Simplified Interior Ballistics of Propellant Actuated Devices," JPL SPS 47-43.

2. Corner, J., "Theory of the Interior Ballistics of Guns," John Wiley, New York, 1950.

3. Hirschfelder, Kershner, and Curtiss, "Interior Ballistics," Volumes I and II, February and April 1943, NDRC Reports A-142 and A-180 (declassified).

4. Kent, R. H., "Some Special Solutions for the Motion of the Powder Gas," Physics 7, 1936.

5. NACA Report 1135, "Equations, Tables and Charts for Compressible Flow," 1953.

6. Serebryakov, M.E., "Interior Ballistics," Moscow 1949, translated at Catholic University of America under Contract NORD 10, 260

7. CPIA, "Solid Propellant Manual," Chamical Propulsion Information Agency, Johns Hopkins University, Silver Spring, Md, 1965 (Confidential).

8. "Internal Ballistics," Philosophical Library, New York, 1951.

9. "Interior Ballistics of Guns," U. S. Army Materiel Command Pamphlet 706-150, February 1965.

10. Heiney, O.K., "A New Computer-Oriented Formulism for Gun Ballistics," Volume II, 3rd ICRPG/AIAA Solid Propulsion Conference Proceedings, CPIA Publication, April 1968.

UNCLASSIFIED

Security Classification

DOCUMENT CONTROL DATA - R & D

(Security classification of title, body of abstract and indexing annotation must be entered when the overall report is classified)

1. ORIGINATING ACTIVITY (Corporate author)	2a. REPORT SECURITY CLASSIFICATION
Air Force Armament Laboratory Air Force Systems Command Eglin Air Force Base, Florida	UNCLASSIFIED 2b. GROUP

3. REPORT TITLE

ANALYTIC AND EXPERIMENTAL INTERIOR BALLISTICS OF CLOSED BREECH GUNS

4. DESCRIPTIVE NOTES (Type of report and inclusive dates)

Final Report

5. AUTHOR(S) (First name, middle initial, last name)

Heiney, Otto K., 1st Lt, USAFR

6. REPORT DATE	7a. TOTAL NO. OF PAGES	7b. NO. OF REFS
May 1969	46	10

8a. CONTRACT OR GRANT NO.	9a. ORIGINATOR'S REPORT NUMBER(S)
b. PROJECT NO 6240509H-2560	AFATL-TR-69-42
c.	9b. OTHER REPORT NO(S) (Any other numbers that may be assigned this report)
d.	

10. DISTRIBUTION STATEMENT This document is subject to special export controls, and each transmittal to foreign nationals or foreign governments may be made only with prior approval of the Air Force Armament Laboratory (ATWG), Eglin Air Force Base, Florida 32542.

11. SUPPLEMENTARY NOTES	12. SPONSORING MILITARY ACTIVITY
Available in DDC	Air Force Systems Command Andrews AFB, Wash, DC 20331

13. ABSTRACT

A closed breech incremental interior ballistic formulism is presented along with a Fortran 4 computer program which utilizes the system. Typical input and output data, both plotted and tabular, are included. A unique characteristic of the system is that it avoids the inaccuracies associated with approximate analytic propellant regression expressions in that regression rates are determined by a tabular routine. Various pressure gradient expressions are investigated. Correlation of the mathematical model and computer predictions to experimental device firings are presented. A shock-driven deflagration effect which may be initiated during the ignition transient is described and a postulated correlation parameter defined.

DD FORM 1 NOV 65 1473

UNCLASSIFIED

Security Classification

Interior ballistics
Ammunition propellants
Guns